BCI - Biology Concept Inventory V1c: Question annotation

minor formatting and modifications – 7 February 2017

Please note: The BCI is designed to give you an idea of what your students are thinking.
Please do not quote questions without explicit acknowledgement

citation: Klymkowsky, Michael W., Sonia M. Underwood, and R. Kathleen Garvin-Doxas. 2010. "Biological Concepts Instrument (BCI): A diagnostic tool for revealing student thinking." *arXiv preprint arXiv:1012.4501*.

Question groups:

Diffusion and drift (Q1, 5, 25, 29, 30)
Energetics and interactions (Q2, 3, 17, 18)
Molecular properties and functions (Q10, 11, 13, 19, 20, 27)
Genetic behaviors (Q7, 15, 16, 21, 22, 23, 24, 28)
Evolutionary mechanisms (Q4, 6, 12, 14, 26)
Experimental design (Q8, 9)

1. Many types of house plants droop when they have not been watered and quickly "straighten up" after watering. The reason that they change shape after watering is because … *Question explores thinking about a commonly observed behavior of plants and looks at whether students understand "passive" osmotic effects versus active mechanisms.*

A. **Water reacts with, and stiffens, their cell walls.** *Response assumes that the cell wall is the sole determinant of plant cell shape and mechanical properties and that active reactions are involved.*
B. **Water is used to generate energy that moves the plant.** *Movement = energy, so the water must directly supply energy to the system for it to move.*
C. **Water changes the concentration of salts within the plant.** *While it is true salt concentrations change, this is not the cause (but an effect) of water movement.*
✔D. **Water enters and expands their cells.** *This is the correct answer and reflects the increased concentration of extracellular water (after watering), which moves into the cells via osmosis.*

2. In which way are plants and animals different in how they obtain energy? *The question examines the extent to which students appreciate the molecular similarities between these two major groups of eukaryotes.*

A. **Animals use ATP; plants do not.** *Students think plants make, but do not use ATP (energy).*
B. ✔**Plants capture energy from sunlight; animals capture chemical energy.** *This is the correct answer; even animals that warm themselves in the sun only use that energy to speed up chemical reactions.*
C. **Plants store energy in sugar molecules; animals do not.** *An idea implanted by common focus on the dichotomy between photosynthesis (plants) and respiration (animals).*
D. **Animals can synthesize sugars from simpler molecules; plants cannot.** *Again, the confusion here is that there are fundamental metabolic differences between plants and animals.*

3. In which way are plants and animals different in how they use energy? *Caveats on questions 2 and 3: student understanding of energy-matter and all of their implications is complex - there is clearly much more research that needs to be done in this area. For example, there are many issues associated with "high energy" bonds and matter/energy interconversion.*

A. **Plants use energy to build molecules; animals cannot.** *The response assumes a fundamental metabolic differences between plants and animals; it focuses on plant's ability to assemble carbohydrates, and animal's need to break down molecules (before assembling new ones).*
B. **Animals use energy to break down molecules; plants cannot.** *The assumption is that plants are "synthesizers" while animals are "consumers". Reflects a failure to recognize the integral linkage between the two.*
C. **Animals use energy to move; plants cannot.** *Assumption that plants are static; clearly energy is required whenever movement (growth) occurs.*
D. ✔**Plants use energy directly, animals must transform it.** *This captures the idea of the difference, but, see caveats above.*

4. How can a catastrophic global event influence evolutionary change? *The question examines the role of random events in evolutionary trajectories. The assumption is that under conditions of rapid change there is no time for standard selective processes to act. It contributes to a picture of students' understanding of random processes as a whole. Students may be able to respond correctly to this question, but then are unable to correctly respond to other questions (even with evolution as the context) that require a grasp and application of what random events and processes mean when they actually occur.*

A. **Undesirable versions of genes are removed.** *Under normal conditions, alleles that negatively impact reproductive success will become less frequent over time. This assumes, however, that many generations are available for the process to occur, which is not the case when we consider catastrophic conditions. Students who select this response ignore the way random events change the "tendency" in evolutionary processes. They are so focused on natural selection, their thinking makes no room for random events. Evolution is a causal system in this model of student understanding and the idea of random events does not resonate.*

B. **New genes are generated**. *In response to environmental change, either gradual or sudden, there is an assumption of a Lamarckian response - the information needed to survive is generated. Students selecting this response recognize that a random event will lead to a change in the pattern of selection. Something different will happen. However, students who select this response are unable to move further along in their thinking. They can apply the idea of random processes to the level of generating new genes, but do not recognize that selective conditions are likely to be significantly altered in the aftermath of such an event. These students do not recognize that this will lead to new evolutionary trajectories.*

C ✔**Only some species may survive the event**. *This response is the most correct, in that it implies that not all species will have the ability to adapt to an unexpected event. In its aftermath, selective conditions are likely to be significantly altered, leading to new evolutionary directions.*

D. **There are short term effects that disappear over time.** *Students who select this response recognize that the event will alter selective conditions, but because it is a catastrophic event, these students see it as something that happens in a snapshot, but then the changes disappear over time and evolution return, presumably unaltered, to the path it was following before the event occurred.*

5. There exists a population in which there are three distinct versions of the gene A (a1, a2, and a3). Originally, each version was present in equal numbers of individuals. Which version of the gene an individual carries has no measurable effect on its reproductive success. As you follow the population over a number of generations, you find that the frequency of a1 and a3 drop to 0%. What is the most likely explanation? *This question is designed to determine whether students, told that specific alleles have no effects on reproductive success but are nevertheless lost over time, recognize that loss is due to a random process, that is genetic drift. Students have an easy time providing a definition of genetic drift, but they do not understand what it means; what it looks like in action – unless it is found in a scenario they are familiar with (e.g., a graph). Students have difficulty with the notion of genetic drift that influences evolution in a population because it is a random process and violates natural selection. Again, their mental models work to align their understanding of natural selection as the driving and causal force behind all evolutionary change. Each of these distracters indicate different ways that students find to explain the effects of genetic drift in terms of natural selection. Random processes as a cause, rarely occurs to them. They do not draw on random processes as an explanation of what occurs in the example because they can't. They can only attempt to explain this scenario using some form of selective processes as the driver.*

A. **There was an increased rate of mutation in organisms that carry either a1 or a3.** *Indicates students think that something "active" is involved in the change. If this were the case, there should be a change in reproductive success; more to the point, there is no reason why the increase in mutation rate per se would lead to the loss of a1 or a3, even if these alleles were detrimental (which we are told is not the case).*

B. **Mutations have occurred that changed a1 and a3 into a2**. *An "active" explanation. The response assumes that there is a directionality to mutation, namely from a1 and a3 to a2, but one might expect a2 to mutate as well (although perhaps not to a1 or a3). There is an implied specificity in the mutation process, for which there is no plausible rationale (except selection, which we have been led to believe does not occur, since there is no measurable difference in reproductive success between organisms carrying the various alleles).*

C. **Individuals carrying a1 or a3 were removed by natural selection.** An "active" explanation. *This would occur if the presence of a particular allele influenced reproductive success. This response suggests a reflex response - allelic change = natural selection. Students who select this response fail to recognize that the gene itself does not have a cause-effect relationship with reproductive success. They are focused entirely on selective conditions as the driving force behind any change in a population (reproductive success = continued existence).*

D. ✔**Random variations led to a failure to produce individuals carrying a1 or a3.** *This is the most correct response, given the data presented, and reflects the fact that in the absence of selection, in a sexual population certain alleles will always disappear due to the randomness of gamete formation and fertilization success.*

6. Natural selection produces evolutionary change by ... *Most students have been exposed to the idea of natural selection. The question is designed to provide a context for other responses in the evolutionary/genetic cluster.*

A. ✔**changing the frequency of various versions of genes.** *This is the basic description of what happens in response to selection, whether natural, sexual, or artificial. Natural selection as a process does not deal with the source of variation.*
B. **reducing the number of new mutations.** *This response reflects a Lamarckian attitude, namely that selection acts directly on the rate at which mutations are produced, rather than on their effects on phenotype. The presumption is typically that since mutations are generally harmful, fewer mutations = better adapted*
C. **producing genes needed for new environments.** *Another Lamarckian presumption, namely that selection acts (creatively) to induce the mutations/traits needed by the organism to adapt to a particular environment/niche.*
D. **reducing the effects of detrimental versions of genes**. *This is a more complex response, in the sense that selection can achieve this result either by removing an allele from the population or by the selection other mutations that ameliorate its effects – overlooks role of selection in maintaining the levels of beneficial alleles.*

7. If two parents display distinct forms of a trait and all their offspring (of which there are hundreds) display the same new form of the trait, you would be justified in concluding that ... *Question places a conventional genetics cross question in unfamiliar terms to see if students can deduce the answer. Since there are many offspring, we can assume Mendelian ratios will apply. This is a question that we might expect to show increased confusion with increased instruction (an assumption that needs to be tested directly).*

A. **both parents were heterozygous for the gene that controls the trait.** *Captures the idea that new trait arises from new combination of alleles, but ignores the observation that all offspring are similar (and different from parents).*
B. ✔ **both parents were homozygous for the gene that controls the trait.** *Only under these conditions will all of the offspring be the same and produce a new form of the trait.*
C. **one parent was heterozygous, the other was homozygous for the gene that controls the trait.** *Two possible classes of offspring would be expected, and one would be the same as one of the parents.*
D. **a recombination event has occurred in one or both parents.** *Technical language used to hide misunderstanding of the question and its answer. Recombination could produce a new trait, but it would not be seen in all of the offspring.*

8. You are doing experiments to test whether a specific type of acupuncture works. This type of acupuncture holds that specific needle insertion points influence specific parts of the body. As part of your experimental design, you randomize your treatments so that some people get acupuncture needles inserted into the "correct" sites and others into "incorrect" sites. What is the point of inserting needles into incorrect places? *The question seeks to explore how well students understand the differences between controls and experiments, and what makes a good control. This is a subject that could easily do with more research and inventory questions.*

A. ✔ **It serves as a negative control.** *This is the correct answer, since needles in the "wrong" places should have no effect given our hypothesis. If they have an effect, we need a new hypothesis.*

B. **It serves as a positive control.** *Indicates that doing something (placing needles) is a positive control. The idea of positive control appears to be quite difficult, since it implies a test for normal, expected function - such as testing an antibiotic for potency on an organism known to be susceptible to it, before testing it on a new (previously untested) organism.*

C. **It controls for whether the person can feel the needle.** *Assumes that something positive is learned. This choice reflects confusion as to what constitutes a control, and examines a variable not identified as significant in the experiment.*

D. **It controls for whether needles are necessary.** *Reflects confusion as to what constitutes a control, and examines a variable not identified as significant in the experiment. In our experience C and D responses are not particularly attractive, compared to B.*

9. As part of your experiments on the scientific validity of this particular type of acupuncture, it would be important to … *Question is aimed at discerning student understanding of what constitutes a scientific question, and how they are answered.*

A. **test only people who believe in acupuncture.** *This assumes that beliefs impact objective assessments; approaches an awareness of the placebo effect - effect occurs because of belief.*

B. **test only people without opinions, pro or con, about acupuncture.** *This assumes that beliefs impact objective assessments. This also assumes that all of acupuncture's effects are due to the placebo - so A and B together tests appreciation of the placebo effect.*

C. **have the study performed by researchers who believe in this form of acupuncture.** *This assumes that beliefs of researchers impact experimental observations - this indicates a more sophisticated view of scientific experiments, associated with the need for double-blind studies; a follow-up question would be appropriate.*

D, **determine whether placing needles in different places produces different results**. *This is a scientific question, which assumes that we are testing a specific prediction of acupuncture's mechanism.*

10. What makes DNA a good place to store information? *The question aims to uncover what it is about the structure of the DNA molecule that is particularly suited for the storage of information. This involves understanding the basic organization of the molecule, how it interacts with water to place the sugar-phosphate backbone in contact with water, how it "hides" the hydrophobic surfaces of the bases, how the structure is, for most practical purposes, independent of base sequence, and how each base determines the identity of the base on the opposing (complementary strand).*

A. **The hydrogen bonds that hold it together are very stable and difficult to break** *This implies that the important information storage aspect of the molecule is the coupling of strands and molecular stability, rather than the independence of the over-all structure on the sequences of bases along a strand.*

B. **The bases always bind to their correct partner**. *This aspect of the structure is important in the context of the replication of genetic information, but not its storage (coding).*

C. ✔**The sequence of bases does not greatly influence the structure of the molecule.** *It is only because the structure of the molecule does not impose significant constraints on the sequence of base pairs that nucleic acid molecules can so easily encode information. If the sequence of bases did influence the structure (as it does in RNA molecules or amino acids in polypeptides), then we would expect that information could be lost due to structural constraints - only if other systems were available to "over-ride" these structural constraints would the information be accessible. In the cell, ribosomes can unfold mRNAs, while folding can render an mRNA unreadable (without other factors).*

D. **The overall shape of the molecule reflects the information stored in it.** *It is true that DNA sequence information can be read by proteins (transcription factors), but they do not (generally) look at overall shape, but rather directly at the sequence of base pairs through complementary surface interactions.*

11. What is it about nucleic acids that makes copying genetic information straightforward? *The question complements question 10 to uncover what it is about the structure of the DNA molecule that is particularly suited for the replication of information.*

A. **Hydrogen bonds are easily broken**. *Reflects the idea that it is weak binding between strands of nucleic acids that is critical. While individual H-bonds are easily broken, in the context of an intact nucleic acid molecule, with thousands to millions of H-bonds, this is not what facilitates replication. In the cell, energy-dependent macromolecular complexes are used to unwind DNA.*

B. ✔ **The binding of bases to one another is specific.** *This is the correct answer. Given the structure of a nucleic acid molecule, once one strand is specified, the complementary strand is also specified. This is quite distinct from the case in proteins, where amino acids play an analogous role. While proteins can, in theory, be formed into a replicatory circuit, it would depend upon a complex reaction sequence rather than on simple complementary interactions between amino acids.*

C. **The sequence of bases encodes information**. *This confuses information storage with replication.While the sequence of bases along the length of the DNA molecule does encode information, it is not this property of the molecule that makes replication so straightforward, rather it is the complementary nature of base-pairing, as captured by Chargaff's rule of the composition of DNA (and not RNA), that is, A=T and C=G.*

D. **The shape of the molecule is determined by the information it contains.** *Idea that somehow shape = information. This is something that needs to be explored further is student understanding of information as a concept, a concept that transcends biological systems.*

12: It is often the case that a structure (such as a functional eye) is lost during the course of evolution. This is because ... *The question aims to uncover the relationship between cost and benefit associated with the evolution / maintenance of any particular trait. A trait, while beneficial, may not be worth the cost to maintain it, if it does not provide a sufficient productive advantage. Alternatively, a trait may be beneficial in one context and not in another. Eyes in the dark may produce distracting information.*

A. **It is no longer actively used.** *Confuses use with selection, like the loss of muscle mass in the absence of exercise. Also, because a trait is not "used" does not mean it will be lost. It is possible that it is produced by another process that does have a selectable function.*

B. **Mutations accumulate that disrupt its function.** *This implies that somehow mutations are targeted to influence a particular trait, a type of reverse Lamarckian perspective. The reason that mutations accumulate (rather than occur) is that they are no longer selected against.*

C. **It interferes with other traits and functions.** *Implies that such a situation could have arise by selection, and reflects some belief in a type of runaway or directional process. Whether it is possible for an organism to have equally and highly acute senses of sight, smell and hearing, or whether there must be compromises in a finite biological system, is unclear. However, if the trait were valuable, and led to differential reproductive success, it would be maintained by natural* selection.

D. ✔**The cost to maintain it is not justified by the benefits it brings**. *In an environment where sight is not important for survival (even though there may be sources of light, e.g. bioluminescence), whether it is maintained or not will be determined by its cost to maintain (relatively high) and the benefits (little or none) associated with its retention. Its loss may actually have advantages - for example, the organism may be better able to concentrate on other sensory inputs.*

13: When we want to know whether a specific molecule will pass through a biological membrane, we need to consider ... *Question addresses student understanding of the key elements involved in the plasma membrane's barrier function.*

A. **the specific types of lipids present in the membrane.** *Assumes that lipids specifically regulate membrane permeability. Ignores role of proteins in permeability (and lipids in impermeability. Which lipids are present does not greatly impact permeability, although it may impact protein function.*

B. ✔ **the degree to which the molecule is water soluble.** *This is the basic determinant of membrane permeability (Overton's law), in the absence of specific protein transporters. A follow up question as to what makes a molecule water soluble would clearly be appropriate.*

C. **whether the molecule is actively repelled by the lipid layer.** *A common misconception that failure to dissolve implies active repulsion. Contrasts with the view that in the absence of the ability to make H-bonds, water "holds" onto hydrophilic molecules.*

D. **whether the molecule is harmful to the cell.** *Assumes that the membrane/cell knows what is harmful, implies an intelligent/purposeful function for the membrane, rather than considering the physical properties controlling permeability.*

14. How might a mutation be creative? *The question examines the common idea that mutations are always harmful and never beneficial. Since the evolution of a new trait depends upon "creative mutations" and their effects on phenotype and reproductive success, and these creative mutations are the result of random changes in DNA sequence, this is another question related the random processes that underlie biological systems.*

A. **It could not be; all naturally occurring mutations are destructive**. *Directly supplies a common student-held assumption. Starts with the molecule as "perfect" and mutations as eroding that perspective.*
B. **If the mutation inactivated a gene that was harmful**. *Here is a variation that, while essential negative in effect, leads to a positive effect through a double-negative mechanism.*
C. ✔**If the mutation altered the gene product's activity**. *Since mutations act through altering either gene product production, activity or stability, this is one of two possible correct choices. While the answer does not specifically reveal how altering the gene product's activity would be creative (e.g. by altering binding partners of catalyzed reactions), it does indicate that the mutation changes, rather than destroys, activity. This choice is common, and further questions on the molecular basis of phenotype would clearly be useful.*
D. **If the mutation had no effect on the activity of the gene product.** *Another variation of the "mutation is not really a significant creative aspect of the evolutionary process" type response. This is generally the most or second most common answer.*

15. An allele exists that is harmful when either homozygous or heterozygous. Over the course of a few generations the frequency of this allele increases. Which is a possible explanation?
The allele ... *Probes student understanding of gene linkage.*

A. ✔ **is located close to a favorable allele of another gene.** *Correct answer, where the benefits associated with one allele more than compensate for the harmful effects of a closely linked deleterious allele.*
B. **has benefits that cannot be measured in terms of reproductive fitness.** *Assumes ill-defined/ unmeasurable benefits; reflects a non-scientific assumption.*
C. **is resistant to change by mutation.** *Confused understanding of the random nature of mutations and the possibility that a mutation could actually reduce the selective disadvantage of a gene.*
D. **encodes an essential protein.** *Confused understanding of nature of the allele and its effect; assumes essential genes are immune from selection.*

16. In a diploid organism, what do we mean when we say that a trait is dominant? *Question addresses understanding of what "dominant" means - analysis is coupled to questions 15, 21 and 24, which examine relationships between allele and trait.*

A. It is stronger than a recessive form of the trait. *Displays some confusion about linkage between molecular change (allele difference) and traits. Implies that there is a battle of some sort between alleles. Capture amorphous idea of "strength".*
B. It is due to more, or a more active gene product than is the recessive trait. *Very much like previous response, more is dominant to less.*
C. The trait associated with the allele is present whenever the allele is present. *This is the basic criteria for dominance, although it is modulated by other factors that can control penetrance and expressivity.*
D. The allele associated with the trait inactivates the products of recessive alleles. *Very much like A and B, where traits are in conflict.*

17. How does a molecule bind to its correct partner and avoid "incorrect" interactions? *This question explores students understanding of the principles of molecular interactions. Few (if any) students have the correct model of molecular bonds minimizing the interaction energy. They mostly resort to either geometric or "action at a distance" explanations.*

A. **The two molecules send signals to each other**. *A response that indicates that molecules are actively involved in finding their "appropriate" partners and ignoring inappropriate partners. This is a typical "action at a distance" answer. The student does not address the question of how (after exchanging signals) the molecules actually bind.*
B. **The molecules have sensors that check for "incorrect" bindings.** *This response suggests that molecules make active decisions about their interactions. A variant of the geometric model. Again the student does not answer the question of how molecules actually bind, although in this case they fail*
to do so by not specifying what constitutes an "incorrect" binding.
C. ✔ **Correct binding results in lower energy than incorrect binding**. *This is the correct answer. The two molecules stay at the relative position that minimizes their interaction energy. Weaker intermolecular interactions are more readily disrupted by collisions with other molecules (thermal effects).*
D. **Correctly bound molecules fit perfectly, like puzzle pieces**. *This is the geometric model, and it does not allow for the fact that chemical affinity is a continuous function. A geometric model is on/off (either the molecules fit like puzzle pieces or they don't). It is hard to reconcile this view with a view of mutations as creative, and may pose a barrier to understanding evolutionary processes and the role of mutations.*

18. Once two molecules bind to one another, how could they come back apart again? *This question is related to question 17 and probes students' understanding of the energetics of molecular interactions. It also relates to the idea of random processes; students often resort to drivers (other reactions, changes in molecular shape). They do not accept the fact that at the molecular levels things happen due to random (stochastic) events.*

A. **A chemical reaction must change the structure of one of the molecules**. *This response suggests both an active (purposeful) and geometric mechanism for dissociation, with a clear cause for disassociation - a chemical reaction. While a reaction can lead to a change in the structure, lower intermolecular affinity and dissociation, this is not always the case.*
B. ✔**Collisions with other molecules could knock them apart.** *This is the correct answer. At the molecular level collisions happen all the time. Some will have enough energy to break the bond(s). The half-life of the complex will then be a function of the binding energy and strength of thermal perturbation.*
C. ❑**The complex will need to be degraded**. *Another active (degradative) mechanism.*
D. **They would have to bind to yet another molecule.** *Another variant of an active driver mechanism. One could argue that a collision with another molecule serves this role, leaving some ambiguity in student thinking - alternatively, they could be thinking about allostery – clearly there is room here for follow-on questioning.*

19. Why is double-stranded DNA not a good catalyst? *Question is designed to probe understanding of what a catalyst must do, as well as understanding of DNAs properties.*

A. **It is stable and does not bind to other molecules.** *A very popular response, it indicates a failure to understand the role of protein-DNA interactions in chromatin packing, gene expression and replication. Assumes that DNA is essentially inert.*
B. ✔**It isn't very flexible and can't fold into different shapes.** *This is the correct response. Double-stranded structure limits geometries available (in contrast to single-stranded RNA).*
C. **It easily binds to other molecules.** *This is the opposite of the assumption expressed in A.*
D. **It is located in the nucleus.** *Suggests that catalysis is a cytoplasmic rather than a cellular process that occurs throughout the cell.*

20. Lipids can form structures like micelles and bilayers because of ... *Question complements question 13 and seeks to reveal student understanding of the principles of membrane formation.*

A. **their inability to bond with water molecules.** *This reflects failure to appreciate amphipathetic nature of lipid molecules; also ignores van der Waals interactions, which take place between all types of molecules (although they can be overwhelmed by molecular charges).*
B. **their inability to interact with other molecules.** *Generalizes on the inability of parts of lipid molecules to form H-bonds with water; ignores the universality of van der Waals interactions.*
C. **their ability to bind specifically to other lipid molecules.** *Assumes that active binding between lipid molecules, rather than their amphipathic nature and interactions with water, are the driving force in supermolecular organization of lipids.*
D. ✔ **the ability of parts of lipid molecules to interact strongly with water.** *This is the correct answer, it recognizes that lipid molecules have different "parts" with different properties.*

21. A mutation leads to a dominant trait; what can you conclude about the mutation's effect? *Examines the extent to which students can recognize the various ways that mutations can produce different phenotypes.*

A. **It results in an overactive gene product.** *While this is possible, it is not necessarily the case (think haploinsufficiency).*
B. **It results in a normal gene product that accumulates to higher levels than normal.** *Again, this is a possiblity.*
C. **It results in a gene product with a new function.** *Again, this is a possiblity.*
D. ✔ **It depends upon the nature of the gene product and the mutation.** *This is the correct and rigorous response and illustrates an appreciation for the complex link between molecular change and phenotypic traits.*

22. How similar is your genetic information to that of your parents? *A relatively simple question on basic Mendelian genetics.*

A. ✔ **For each gene, one of your alleles is from one parent and the other is from the other parent.** *This is the correct response*
B. **You have a set of genes similar to those your parents inherited from their parents.** *Ignores effects of independent assortment and crossing over and recombination.*
C. **You contain the same genetic information as each of your parents, just half as much.** *Suggests an assumption of a blended type of inheritance*
D. **Depending on how much crossing over happens, you could have a lot of one parent's genetic information and little of the other parent's genetic information.** *Invokes a "high tech" answer for a (basically) simple process, and gets the end result wrong.*

23. Question: 23 (modified) An individual, "A", displays two distinct traits. A single, but different gene controls each trait. You examine A's offspring, of which there are hundreds, and find that most display either the same two traits displayed by A, or neither trait. There are, however, rare offspring that display one or the other trait, but not both. *Examines the extent to which students can recognize the linkage of genes (such as the two traits described here) and how the probability of recombination (separation) depends upon their proximity along the chromosome.*

A**. The genes controlling the two traits are located on different chromosomes.** *Ignores the observation that the traits are generally inherited together.*

B**. ✔ The genes controlling the two traits are located close together on a single chromosome.** *Recognizes the significance of the observation that the traits are most commonly inherited together (and so are linked on a chromosome), but that meiotic recombination can act to separate them.*

C**. The genes controlling the two traits are located at opposite ends of the same chromosome.** *Fails to recognize that below a certain distance along the chromosome (50 centimorgans), the traits will appear unlinked.*

24. A mutation leads to a recessive trait; what can you conclude about the mutation's effect? *This question explores student understanding of the relationship between genotype and phenotype. It uses the standard recessive (and dominant - see question 21) terminology, and seeks to determine whether students understand that this behavior is not, in and of itself, sufficient to make conclusions about the nature of the molecular defect involved.*

A. **It results in a non-functional gene product.** *While this may well be the case, we are not justified in assuming that all recessive mutations influence a particular phenotypic trait in this manner. It also suggests a belief that all mutations produce non-functional gene products, ignores the possibility that the mutant gene product is simply less functional (technically hypomorphic).*

B. ❑**It results in a normal gene product that accumulates to lower levels than normal.** *While this could well be the case, we are not justified in making this conclusion - further data is necessary.*

C. **It results in a gene product with a new function.** *Again, while this could well be the case, we are not justified in making this conclusion - further data is necessary.*

D. ✔**It depends upon the nature of the gene product and the mutation**. *Exactly.*

25. Imagine an ADP molecule inside a bacterial cell. Which best describes how it would manage to "find" an ATP synthase so that it could become an ATP molecule? *This question explores student understanding of the fact that random, i.e., diffusive, processes underlie most molecular movement in cells.While the language may seem "expert-like", it is in fact the language used by students.*

A. **It would follow the hydrogen ion flow**. *This response indicates an active movement of molecules along a gradient toward the ATP synthase. Student think that since a hydrogen ion gradient is involved in ATP generation, it (rather than diffusion) plays a role in bringing all of the reactants, such as ADP and phosphate, to the enzyme.*

B. **The ATP synthase would grab it.** *This response assumes an active (rather than diffusive) process brings reactants to the enzyme. Such a mechanism is commonly found in illustrations/movies of enzymatic processes. It is another manifestation of the "action at a distance" concept (cf. question 17).*

C. **Its electronegativity would attract it to the ATP synthase**. *Again, this response assumes an active (rather than diffusive) process that brings reactants to the enzyme, and it supplies a mechanism - electronegativity, which is a term used to compare atoms in a bond and not molecules as a whole. Electric fields can lead to higher local concentrations of molecules, as occurs when there is a membrane potential/electrical field across a membrane, but these effects require large fields and are limited in their range. Another variant of "action at a distance"; students do not understand that chemical reactions involve very short-range interactions.*

D. ❑**It would be actively pumped to the right area**. *Again, this response assumes an active (rather than diffusive) process brings reactants to the enzyme, and it supplies a mechanism - "pumping", presumably related to the pumping of H^+ across the membrane or because the ATP synthase can act as a pump when running "backwards".*

E. ✔**Random movements would bring it to the ATP synthase**. *Students understand that most molecules move via diffusive/random mechanisms within the cell. Again, this response captures an understanding that random processes can be effective actors.*

26. You follow the frequency of a particular version of a gene in a population of asexual organisms. Over time, you find that this version of the gene disappears from the population. Its disappearance is presumably due to ... *Question examines understanding of the difference between asexual organisms, in which all alleles are transferred to progeny and sexual organisms where this is not the case.*

A. **genetic drift** *In asexual organisms, a version of genetic drift occurs when population size fluctuates, and survival is not related to reproductive success. Should be probed with follow up question.*

B. ✔ **its effects on reproductive success.** *This is presumably the cause of the change.*

C. **its mutation.** *Mutation = change, assumes that similar mutations occur in a number of independent lineages, which is unlikely.*

D. **the randomness of survival.** *This is a version of drift that would be unlikely unless the population size fluctuated dramatically. Should be probed with follow up question.*

27. Consider a diploid organism that is homozygous for a particular gene. How might the deletion of this gene from one of the two chromosomes produce a phenotype? *As in the case of the recessive/dominant questions, we are looking to understand student thinking about the relationship between genotypic and phenotypic changes. Students need to think about how gene copy number influences level of gene product and whether a particular gene is haploinsufficient.*

A. **If the gene encodes a multifunctional protein**. *The particular function of a gene product does not, in and of itself, determine whether the loss of one copy will lead to a phenotype.*
B. ✔ **If one copy of the gene did not produce enough gene product**. *This is the simplest and most correct explanation. This could lead to a number of possible "down-stream" effects.*
C. **If the deleted allele were dominant**. *Genes are not dominant or recessive, traits are. That said, it is common for students to think in terms of human like agency, with one allele being more powerful than the other. In this case, the student assumes that the genetic locus in question is heterozygous, since this response would not make sense if the locus were homozygous.*
D. **If the gene encoded a transcription factor.** *The particular function of a gene product does not, in and of itself, determine whether the loss of one copy will lead to a phenotype, but students may imagine that transcription factors have more powerful effects than other types gene products.*

28. Gene A and gene B are located on the same chromosome. Consider the following cross: AB/ ab X ab/ab. Under what conditions would you expect to find 25% of the individuals with an Ab genotype. *Question address whether students appreciate that the extent of recombination increases with separation of genes on a chromosome up to a maximum level.*

A. **It cannot happen because the A and B genes are linked.** *Indicates failure to appreciate recombination.*
B. **It will always occur, because of independent assortment.** *Confuses two distinct processes, since it will occur only if the genes are far enough away from one another.*
C. ✔**It will occur only when the genes are far away from one another.** *correct*
D. **It will occur only when the genes are close enough for recombination to occur between them.** *Confuses the relationship between recombination and distance between genes.*

29: Sexual reproduction leads to genetic drift because ... *A question to explore understanding about the mechanism of drift.*

A. **there is randomness associated with finding a mate.** *While finding a mate may involve a degree of randomness, if all alleles were transmitted, there would be no genetic drift.*
B. ✔ **not all alleles are passed from parent to offspring.** *correct*
C. **it is associated with an increase in mutation rate.** *A non-random explanation that implies an active mechanism to explain drift.*
D. **it produces new combinations of alleles.** *This is certainly the case, but if all alleles were transmitted, drift would not occur.*

30. How is genetic drift like molecular diffusion? *Based on our research, it is clear that students tend to view diffusion as a directional process - molecules are directed to move in particular directions due to gradients, etc. This question aims to determine whether they see the commonality between two basically random processes.*

A. **Both are the result of directed movements**. *Captures the idea that all changes in biological systems are inherently directional, that is, moving toward a goal.*

B. **Both involve passing through a barrier.** *A common response from students is to view diffusion in terms of membranes or barriers. In a sense this response seeks to determine if the barrier (a kind of direction) also influences students conceptualization of genetic drift.*

C. ✔ **Both involve random events without regard to ultimate outcome**. *At its base, both diffusion and genetic drift are due to random processes, the collisions impacting on a molecule versus the chance that a gamete makes it to the next generation (whether or not it provides a selective advantage).*

D. **They are not alike. Genetic drift is random; diffusion typically has a direction**. *This response directly addresses the common view that diffusion is directional. It is our observation that students are much less likely to have strong ideas about genetic drift, perhaps because they are not so often confronted with the concept in a problem solving context. They may not actually be taking the idea of randomness with regard to genetic drift seriously.*